

# Conceptual Design Studies of Large-Aperture Nb<sub>3</sub>Sn Quadrupoles for LHC Luminosity upgrade at Fermilab

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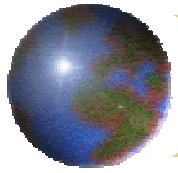
Outlines:

- What do we know about 2<sup>nd</sup> generation LHC IR
- Summary of 90-mm Nb<sub>3</sub>Sn IRQ parameters
- Aperture limitation studies

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*WAAM, Archamps,  
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## *LARP magnet R&D*

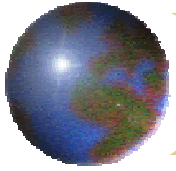


Fermilab participates in the U.S. LHC Accelerator Research Program (LARP) focusing on 2<sup>nd</sup> generation IR magnets for LHC to replace the 1<sup>st</sup> generation magnets:

- limited lifetime (~6 years)
- one of the limiting systems for machine performance

Contributions of Fermilab to LARP Magnet R&D include:

- conceptual designs studies of various magnet types for 2<sup>nd</sup> generation LHC IRs (luminosity upgrade)
- Fermilab will also participate in short and long model magnet R&D as well as in the design, fabrication and tests of full-scale prototypes of the LHC IR magnets



## *IR design approaches*

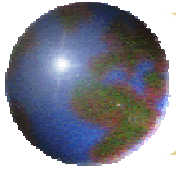


Two approaches to the LHC high-luminosity inner triplet upgrade:

- present inner triplet optic layout with
  - new single, large-bore high gradient quadrupoles
  - new strong correctors
- new inner triplet optic layout with
  - twin, large-aperture high-gradient quadrupoles
  - strong correctors
  - very high field separation dipoles

In all upgrade scenarios one needs new quadrupoles and strong correctors.

Now we focus on the 2<sup>nd</sup> generation quadrupoles - the most complicated and expensive system.

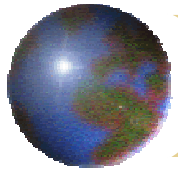


## *IRQ target parameters*



Although the final triplet design and magnet requirements are not completely known at present time the target parameter ranges for IR quads are quite well understood:

- Larger bore –  $D > 90$  mm
- Higher field gradient –  $G_n = 205$  T/m
- Better field quality (or more correctors)
- Larger operation (temperature) margin
- Longer lifetime

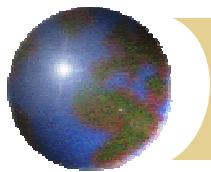


# *Magnet bore & Superconductor*



The preliminary studies performed at Fermilab in 2000-2001 have shown that:

- an increase of magnet aperture from 70 mm to at least 90 mm is one of the most straightforward ways to the luminosity upgrade
  - $\beta^*$  reduces from 50 cm to 25 cm
- the new quadrupoles need superconductor with higher than NbTi critical parameters to increase magnet quench margin
- Nb<sub>3</sub>Sn is a real candidate for these magnets
  - acceptable properties
  - produced on the commercial level
  - reasonable price



## 90-mm IR quadrupole



The results of conceptual design studies performed in 2001-2002 have shown that 90-mm Nb<sub>3</sub>Sn low-beta quadrupoles are feasible and allow reaching the following parameters:

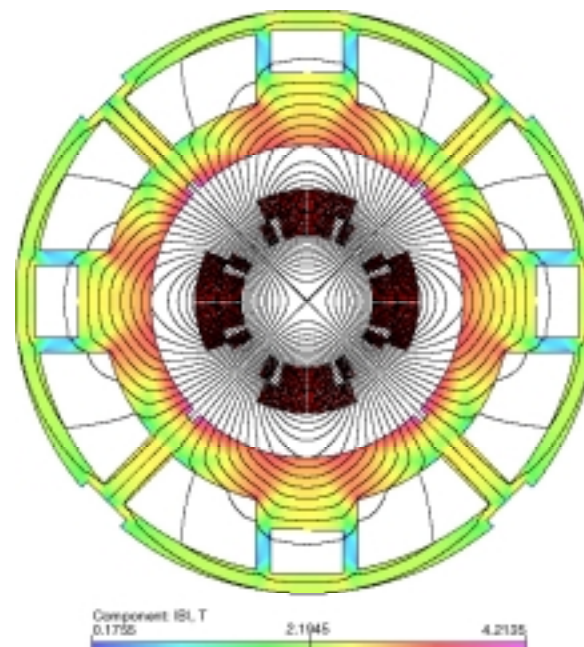
- Nominal gradient 205 T/m @ 1.9K or 4.5K
- 20% I<sub>c</sub> margin with available Nb<sub>3</sub>Sn strands
- Quench margin of 5 (Top=4.5K) or 10 (Top=1.9K)
- Field quality as in present MQXB or better

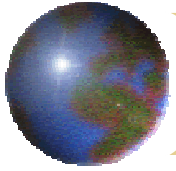
Large holes are used for the longitudinal heat transfer inside the cold mass.

Thick “standalone” stainless steel collar provides coil mechanical support.

The cable has 42 strands each 0.7 mm in diameter.

Quench protection is provided with traditional internal quench heaters.





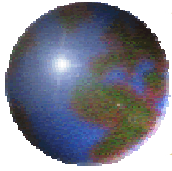
## *Aperture limitations*



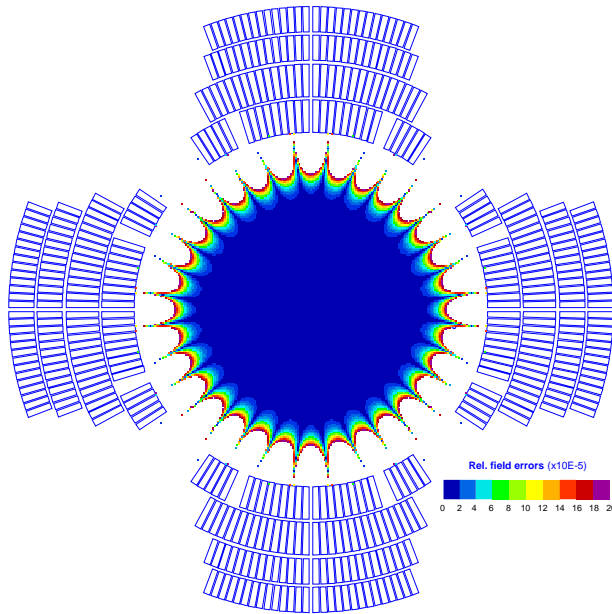
What are the aperture limitations for the Nb<sub>3</sub>Sn quadrupoles?

What are the limiting factors?

- Strand and Cable parameters
- Coil design
- Field quality
- Maximum field in the coil
- Margins
- Maximum stress in the coil
- Quench protection

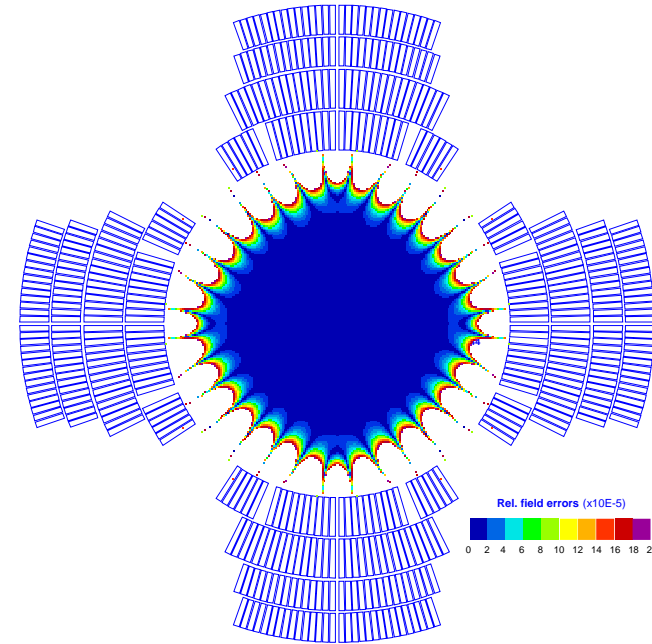


# Coil design



100-mm aperture

- 4-layer design with cold iron yoke
- One wedge in the innermost layer
- Graded coil



110-mm aperture

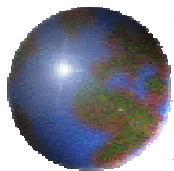
*Coil design looks OK. We have some experience with 4-layer design (KEK MQXB, D20)*

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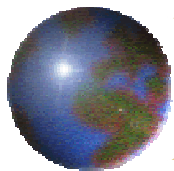


## Strand and Cable



Parameter	100 mm		110 mm	
	Inner	Outer	Inner	Outer
Number of strands	18	14	24	18
Strand diameter, mm	1.000	1.000	1.000	1.000
Cable bare width, mm	9.23	7.16	12.33	9.23
Inner edge thickness, mm	1.612	1.671	1.587	1.662
Outer edge thickness, mm	1.917	1.858	1.943	1.867
Cabling angle, deg	14.5	14.5	14.5	14.5
Keystone angle, deg	1.893	1.495	1.655	1.273
Average packing factor, %	89.0	89.0	89.0	89.0
Inner edge compression, %	19.4	16.4	20.6	16.9
Outer edge compression, %	4.1	7.1	2.8	6.6
Width compression, %	0.0	0.0	0.0	0.0
Copper to non-copper ratio	1.2	1.2	1.2	1.2

*Cable parameters in both cases look OK.*



## Field quality



Geometrical harmonics.

n	$b_n$ @ 17 mm			$b_n$ @ $R_{\text{bore}}/2$			$b_n$ @ 17 mm
	110 mm	100 mm	90 mm	110 mm	100 mm	90 mm	70 mm*
6	0.00003	0.00011	0.00018	0.00022	0.00053	0.00056	-0.013
10	0.00007	0.00013	0.00048	0.00333	0.00286	0.00451	-0.001
14	0.00004	0.00004	0.00024	0.01179	0.00456	0.00691	-0.0011

\* MQXB

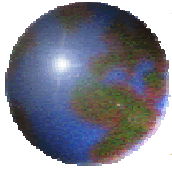
Field quality is OK:

- Geometrical harmonics are comparable with harmonics in MQXA/MQXB; they can be further improved introducing additional wedges in the coil.
- Coil magnetization effect can be reduced using the Nb3Sn strands with small  $d_{\text{eff}}$  and further compensated with a passive correction.
- Iron saturation effect can be minimized using correction halls.

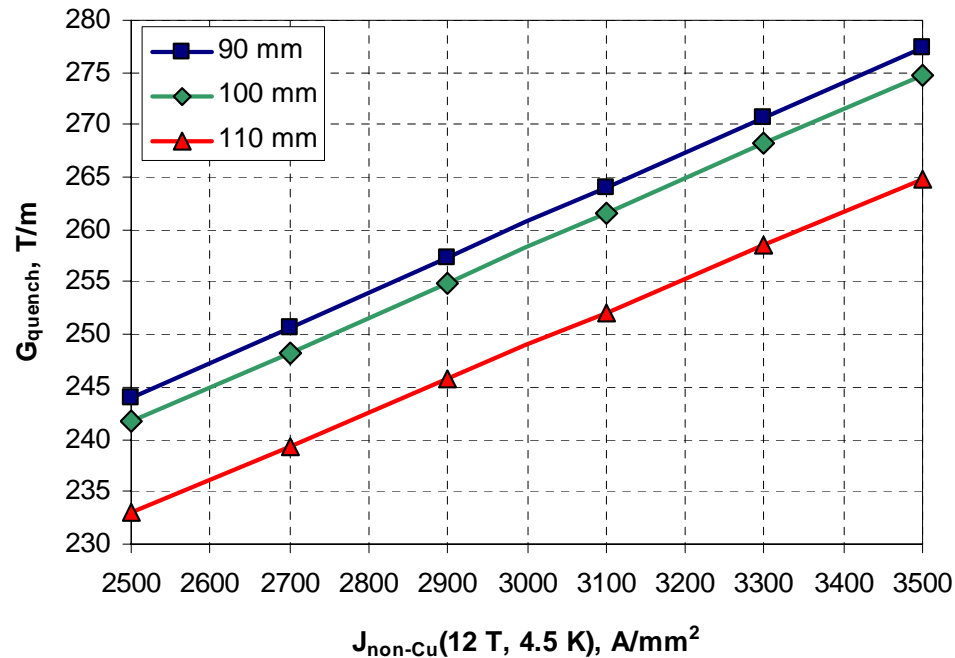
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# Field gradient margin



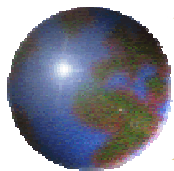
D, mm	Gm(3kA/mm <sup>2</sup> ), T/m	I <sub>c</sub> (3kA/mm <sup>2</sup> ), kA	B <sub>max</sub> , T	J <sub>c</sub> (250T/m), kA/mm <sup>2</sup>
90	260.6	17.64	13.5	2.68
100	258.2	12.31	14.51	2.75
110	248.9	14.13	<b>15.28</b>	<b>3.3</b>

*Attention! B<sub>max</sub> approaches 15 T, required J<sub>c</sub>(12T, 4.2K) > 3 kA/mm<sup>2</sup>.*

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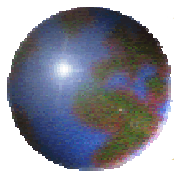
## Mechanical parameters



Lorentz forces and maximum coil stress.

Parameter		Unit	Aperture		
			110 mm	100 mm	90 mm
Lorentz forces in the first octant at $G_{nom}=205$ T/m	$F_x$	MN/m	3.44	2.38	1.5
	$F_y$	MN/m	-3.42	-2.39	-1.92
Maximum coil stress		MPa	<b>99</b>	<b>90</b>	73

*Attention! Lorentz forces and stress in the coil reach dangerous level. Adequate mechanical solution has to be found.*



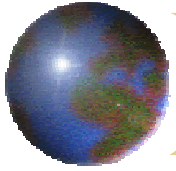
# Quench protection



Quench protection parameters.

Parameter		Unit	Aperture size		
			110 mm	100 mm	90 mm
Inductance		mH/m	17.46	14.71	4.86
Stored energy at G=205 T/m		kJ/m	1181.4	702.9	468.2
Coil maximum temperature during quench, $T_{hs}/T_{blk}$	$F_{qh}=50\%$	K	230/150	225/140	230/127
	$F_{qh}=25\%$	K	335/220	320/200	315/180

*Although the storage energy and magnet inductance significantly increase for the 4-layer design and large aperture, the quench protection parameters look still OK.*



## Summary



The 110 mm quadrupoles can provide the maximum field gradient of 250 T/m and acceptable field quality.

Analysis shows that with these magnets  $\beta^*$  can be reduced by a factor of 3, from 50 cm to 17 cm.

Quench protection of these magnets can be provided using the traditional approach based on internal quench heaters.

However,

- The 20% critical current margin requires the R&D Nb<sub>3</sub>Sn strands with  $J_c(12\text{T}, 4.2\text{K}) > 3 \text{ kA/mm}^2$ .
- The peak field in the coil at quench exceeds 15 T.
- The Lorentz forces in the coils are large so that the maximum coil stress approaches to the level of 100 MPa (can be even higher during magnet assembly).

The risks associated with the above factors have to be analyzed and taken into account while choosing the final quadrupole aperture.